Phase II Project Summary

Firm: CFD Research Corporation
Contract Number: NNX11CB02C
Project Title: Software for Automated Generation of Reduced Thermal Models for Spacecraft Thermal Control

Identification and Significance of Innovation:
Accurate, efficient thermal analysis is a well-recognized challenge for precise spacecraft design and control. Current thermal analysis relies on either full-scale, high-fidelity computations or simplified analytical models. These approaches are either computationally prohibitive (such as the STOP-G analysis of LISA in a single model topology) or inadequate in accuracy, and require a significant level of expertise from spacecraft design engineers, leading to substantial cost overruns and delays in spacecraft development. Therefore, there is a clear and unmet need for a software tool that can automate the generation of mathematically rigorous, reduced thermal models to enable order-of-magnitude savings in computational resources and time leading to efficient spacecraft design. The integrated Model Order Reduction (MOR) tool developed in the Phase II specifically addresses such computational challenges. Key innovations that mark this effort include:

- ***Mathematically proven, projection-based, data-driven MOR*** approaches to enable automated generation of reduced models and to address strong nonlinear thermal effects in spacecrafts
- A verification module to automate the comparison of reduced thermal models against large models
- ***A modular software framework*** to seamlessly integrate the entire process of MOR, reduced model computation, and verification into the NASA-relevant thermal analysis tool

Our MOR software delivers NASA engineers a valuable tool to perform rational and computationally affordable analysis, develop reliable thermal control strategies for spacecrafts, and greatly reduce the development cycle times and costs.

Technical Objectives and Work Plan:
The overall objective of the project is to develop robust model order reduction (MOR) algorithms and software to significantly and automatically reduce the computational orders of large thermal models for precise thermal analysis/design of delicate instruments and spacecrafts. Specific Phase II technical objectives and work plan are:

- Develop novel MOR algorithms to enhance speed, accuracy, and stability of the software
- Develop new MOR capabilities to address complex thermal models
- Develop novel nonlinear parameterized MOR algorithms for enhanced ROM reusability
- Develop a modular software environment to integrate our MOR software into NASA-relevant thermal analysis tool
- Validate and demonstrate MOR software for large-scale, complex spacecraft thermal analysis of NASA interest

Technical Accomplishments:
All Phase II goals were successfully accomplished, including:

1. Various nonlinear equation-based, parameterized MOR methods and equation-free (data-driven) algorithms were investigated with respect to multiple criteria (such as accuracy, stability, computational cost, amenability to commercial software integration).
   a. In the category of equation-based MOR, Proper Orthogonal Decomposition (POD)-based MOR and Trajectory Piecewise Linear MOR (TPWLMOR) were identified and selected as the most appropriate candidates due to their salient capabilities and accuracy of addressing strong nonlinear effects encountered in spacecraft heat transfer.
   b. For equation-free MOR, Radial Basis Function (RBF) based algorithms were explored to circumvent the matrix assembly process of reduced modeling in SINDA/FLUINT and to facilitate and accelerate the multi-orbit thermal analysis.
   c. Accordingly, our MOR software provides a variety of reduction algorithms and engines (POD, TPWLMOR, and RBF) to enable efficient reduction of computational cost in various spacecraft thermal models and simulation scenarios, and further enhance the utility of the software.
2. A Differential-Algebraic Equation (DAE) was developed to handle the massive-size equation system for equation-based MOR. The large size and difficulty to determine the Jacobian pattern of models with heaters renders the Matlab's built-in Differential Algebraic Equation (DAE) solver ODE15s and ODE23t intractable. To address the issue, we developed an in-house solver based on the Crank-Nicolson temporal differencing scheme that converts the DAE equation set into a linearized algebraic equation set for computationally manageable solution.
3. The modular simulation environment was established to integrate the abovementioned key components and streamline the whole process. A verification module was also developed to compare results of reduced order models against the full scale, large model data.
4. A data exchange interfaces and two numerical libraries, respectively, for the equation-based and equation-free MOR were developed to integrate our software into NASA-relevant thermal analysis tool (SINDA/FLUINT developed by C&R Tech), through which we could demonstrate our MOR capabilities to tackle spacecraft thermal analysis of NASA interest and general heat transfer studies.
   a. An equation-based MOR Fortran library was developed and integrated with SINDA/FLUINT. The library reduces the computational cost associated with the solution of the linear algebraic equations in SINDA/FLUINT. Due to the difficulty to collect beforehand the original model matrices (e.g., conductor array, heater information, etc.), such a software integration strategy relies on the time-consuming matrix assembly process during each iteration, leading to limited speed up.

    b. An equation-free MOR Fortran library was developed for SINDA/FLUINT integration to obviate the expensive matrix assembly process. The equation-free library can bypass model assembly to achieve higher computational acceleration and facilitate integration with third-party analysis tool (but at the cost of larger simulation error).
5. Graphical User Interface (GUI) development of MOR Software. GUI has been developed for our MOR software. The primary objective of this GUI is to allow users to select the type of ROM analysis that has to be performed, and if required, select appropriate interpolating functions, training data files and the associated display options.
6. Finally, the utility of our MOR software and libraries to NASA applications was demonstrated by performing whole-satellite thermal analysis (LISA, JETS, and GPM models). The study demonstrated that our MOR software can achieve salient reduction in computational times/costs while retaining good accuracy relative to the full-scale models. Depending on the methods (parameterized and equation-based or equation-free approach), speed up ranging from 3X−500X with the relative error <5% can be achieved using our MOR software.

Our Phase II study provided comprehensive evidence and demonstration that **reduced thermal models can be used for rapid and accurate thermal analysis and spacecraft design being actively pursued by NASA researchers.**

NASA Application(s):
Based on the challenges identified in the original solicitation, the NASA applications of our MOR software are evident. The NASA Vision for Space Exploration and Earth Science calls for the development of sophisticated thermal control technology to address the harsh space environment and the increasingly demanding operational requirements of spacecrafts during exploration. Therefore, it is essential to develop a MOR framework capable of automatically generating accurate, reduced thermal models that can be consistently used for engineering of spacecrafts at every stage including design, test, ground-operation simulation, and controller development. The developed MOR algorithm and software will deliver NASA engineers a valuable tool to (1) perform rapid and computationally affordable thermal analysis for better understanding of design spaces, (2) develop advanced, reliable thermal control strategies for spacecrafts and instruments, and (3) arrange test procedures for rational use of instruments and facilities. The success in the research will markedly reduce the development cycles of spacecrafts.

Non-NASA Commercial Application(s):
The non-NASA markets and customers of our MOR technology are varied and include various government and commercial applications. For instance, among government customers, US Air Force is seeking a flexible, module thermal control management methodology for Operationally Responsive Space (ORS) Satellites. In the commercial sector, applications exist in semiconductor industry, combustion, power and aerodynamics industry, chemical plants, biomedical companies, micro-electro-mechanical systems (MEMS) and microfluidics manufacturers. This spans diverse applications such as rapid thermal processing (RTP) systems, combustion and propulsion devices, structure design and fatigue analysis, distributed reacting systems (e.g., chemical vapor deposition), and biochip devices. The effort would directly contribute to these vital areas by providing a powerful tool to generate fast reduced order models, which can be extensively used to (1) analyze the industrial processes for fault diagnostics and optimized design (e.g., more effective utilization of existing technologies and the development of new technologies); and (2) develop advanced controller strategies for online process monitoring and control.

Name and Address of Principal Investigator:
Yi Wang, Ph.D., CFD Research Corporation, 701 McMillian Way NW, Suite D, Huntsville, AL 35806

Name and Address of Offeror:
CFD Research Corporation, 701 McMillian Way NW, Suite D, Huntsville, AL 35806